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LETTER

The influence of soil moisture deficits on Australian heatwaves

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**Abstract**

Several regions of Australia are projected to experience an increase in the frequency, intensity and duration of heatwaves (HWs) under future climate change. The large-scale dynamics of HWs are well understood, however, the influence of soil moisture deficits—due for example to drought—remains largely unexplored in the region. Using the standardised precipitation evapotranspiration index, we show that the statistical responses of HW intensity and frequency to soil moisture deficits at the peak of the summer season are asymmetric and occur mostly in the lower and upper tails of the probability distribution, respectively. For aspects of HWs related to intensity, substantially greater increases are experienced at the 10th percentile when antecedent soil moisture is low (mild HWs get hotter). Conversely, HW aspects related to longevity increase much more strongly at the 90th percentile in response to low antecedent soil moisture (long HWs get longer). A corollary to this is that in the eastern and northern parts of the country where HW-soil moisture coupling is evident, high antecedent soil moisture effectively ensures few HW days and low HW temperatures, while low antecedent soil moisture ensures high HW temperatures but not necessarily more HW days.

1. Introduction

Heatwaves (HWs) are a frequent occurrence in many parts of northern and eastern Australia and are projected to increase in frequency, intensity, and duration under future climate change (Cowan *et al* 2014). The occurrence of HWs in Australia has been linked to numerous modes of variability (Cai *et al* 2009, Marshall *et al* 2014, Parker *et al* 2014b) as well as teleconnections which reinforce HW-like conditions (Pezza *et al* 2012, Parker *et al* 2013, 2014a). HWs are also influenced by land surface conditions, namely soil moisture, with several observational studies focusing on Europe (Hirschi *et al* 2011) and globally (Mueller and Seneviratne 2012), showing strong correlations between the number of HW days and dry soils. The suggested physical mechanism linking soil moisture and HWs is a positive feedback whereby dry soils intensify upper level anticyclonic anomalies due to higher sensible heat flux, which in turn leads to higher temperatures at the surface (Fischer *et al* 2007).

Over Australia, changes in rainfall due to the El Niño-Southern Oscillation strongly influences soil moisture availability, which can enhance the seasonal predictability of land surface temperatures (Jones and Trewin 2000). Additionally, positive phases of the Indian Ocean Dipole, which lead to lower rainfall over Eastern Australia and associated dry soil conditions, have been linked to extreme heatwave conditions (Cai *et al* 2009). Timbal *et al* (2002) have also shown that it is necessary to capture soil moisture availability over Australia in order to accurately resolve atmospheric variability. Similar results have been found by Hirsch *et al* (2014) who showed that realistic soil moisture initialisation in models improves the predictability of maximum temperatures in southeast Australia, at lead times of up to 16–30 days. While these studies have generally considered the links between soil moisture and the predictability or variability of near surface temperatures, few studies have explicitly focused on links between soil moisture and HW events in Australia. Such a focus helps bridge the gap between the

Table 1. Heat wave (HW) aspect definitions, calculated monthly. From PA13.

HW aspect	Definition
HWF (Heat wave frequency)	The number of days that contribute towards a HW.
HWM (Heat wave magnitude)	The mean temperature across all HWs.
HWA (Heat wave amplitude)	The peak daily temperature of the warmest HW (as defined by HWM).
HWD (Heat wave duration)	The length of the longest HW.
HWN (Heat wave number)	The number of distinct HWs (of at least 3 or more days each, see text).

effects of soil moisture deficits on the climate system and their potential effects on society.

Nicholls and Larsen (2011) showed that daily maximum temperatures can be up to 1 °C–3 °C higher after droughts over southeast Australia when winds are northerly (from over the land), typical of the extreme high temperatures experienced during early February 2009 in the state of Victoria in southeast Australia. Kala *et al* (2015) investigated the effects of soil moisture perturbations applied 5, 10 and 15 days prior to the same HW event in February 2009 in Victoria. They showed that the influence of soil moisture perturbations is only predictable at a lead time of 5 days, with drier soils leading to higher maximum temperatures and the converse for wetter soils. At longer time frames of 10–15 days, they showed it is not possible to relate a perturbation in soil moisture to a change in temperature, as the imposed perturbation, mostly confined to the northern parts of Australia, is essentially lost within the first 5 to 10 days. Perkins *et al* (2015) investigated the influence of climate variability and soil moisture on HWs in Australia. They used standardised rainfall anomalies computed 5 months prior to the heatwave season (June–October) as a proxy for antecedent soil moisture. These authors showed that the relationship between soil moisture and HWs is rather heterogeneous over Australia and differs between HW aspects.

The work presented here builds substantially upon these studies. The study of Nicholls and Larsen (2011) only used temperature data at a single station in Victoria, and did not explicitly relate soil dryness to the number of HW events, as has been done elsewhere (e.g., Hirschi *et al* 2011). Kala *et al* (2015) only considered a single HW event and focussed on soil moisture up to 2 weeks before that event, rather than long-term drought. Perkins *et al* (2015) examined the influence of precipitation anomalies 5 months prior to the Austral summer on HW events in Australia. However, better methods exist to quantify antecedent soil moisture in a way which takes into account a region's rainfall climatology as well as changes in evapotranspiration—an important variable under a changing climate as increasing temperatures lead to increased evaporation which amplifies droughts (e.g. Sheffield and Wood 2008). Furthermore, none of the above Australian studies examine how the tails of the probability distribution respond to changes in antecedent soil moisture, which is critical in forecasting

risk. Here we address this knowledge gap by using the standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano *et al* 2010) to investigate the spatial relationships between antecedent soil moisture and HW characteristics across the upper, middle and lower parts of their distributions.

2. Methods

2.1. Data

We used gridded observations of daily minimum and maximum 2 metre air temperature, as well as daily precipitation, produced by the Australian Water Availability Project (Jones *et al* 2009; hereafter AWAP) at a resolution of approximately 50 km × 50 km. This dataset has been widely used for the study of HWs in Australia and is considered the authoritative dataset for 20th century Australian climatology (Perkins and Alexander 2013, Perkins *et al* 2015). However, there are known deficiencies in AWAP's representation of extreme precipitation in regions of low station coverage (King *et al* 2013). These data-sparse regions exist predominantly in the arid interior of the continent and we thus remove these areas by requiring each grid cell to have at least 96% non-missing data. Furthermore, due to temperature inhomogeneities and the generally poorer data coverage prior to 1957 (Jones *et al* 2009) we limit our study to the period 1957–2012.

2.2. HW definition

To explore the impact of soil moisture deficits on HW's we utilised the HW definitions outlined by Perkins and Alexander (2013), hereafter PA13. PA13 reconciled the sectoral need for multiple HW definitions with the benefits of a consistent monitoring framework and defined a HW event as three or more days where either: (1) daily maximum temperature exceeds the 90th percentile (Tx90), (2) daily minimum temperature exceeds the 90th percentile (Tn90), or (3) the excess heat factor (EHF) is positive. EHF combines a measure of acclimatisation with a measure of excess heat by comparison of the previous three day mean of daily mean temperature to the preceding month, with a comparison of the previous three day mean of daily mean temperature to the climatological 90th percentile. PA13 further outlined five relevant HW aspects which are calculated here on a monthly basis. These aspects include the HW: amplitude (HWA), magnitude (HWM), duration (HWD), frequency (HWF)

and number (HWN) and are defined in table 1. HWA and HWM are measures of HW intensity, while HWD, HWF and HWN are measures of HW longevity. In this study we focus only on the Tx90 definition of HWs (discussed further in section 2.4). The base period used for calculating percentiles for our HW definitions is 1961–1990, which is the standard base period adopted by the World Meteorological Organization and commonly used by several studies focusing on HWs (Perkins *et al* 2015). Additionally, our conclusions remain robust when the HW indices are calculated using a substantially different base period of 1931–1960 (not shown).

2.3. SPEI

We use the SPEI (Vicente-Serrano *et al* 2010) calculated at a 3 month time scale as a proxy for soil moisture. SPEI is an extension of the Standardised Precipitation Index (SPI; McKee *et al* 1993) which uses standardised comparisons of monthly precipitation with climatological precipitation as an indication for dry or wet conditions. The SPEI extends this by including estimated evapotranspiration in its moisture balance and hence provides a more realistic estimate of soil moisture compared to SPI. This is particularly important under global warming as increased evaporation has the potential to markedly increase the severity of droughts (Alexander 2011). Inputs required for calculating the SPEI are daily precipitation and daily mean temperature (calculated here from AWAP daily minimum and maximum temperatures), both of which are used to calculate evapotranspiration via the Hargreaves method (see Vicente-Serrano *et al* 2010 for details). The SPI/SPEI can be computed at different time-scales, typically between 1 and 12 months. The strongest correlations occur between HW aspects (table 1) and the 3 month SPEI (figure S1), consistent with previous studies (Mueller and Seneviratne 2012, Whan *et al* 2015) and hence we focus our analysis on the 3 month SPEI.

2.4. Methodology

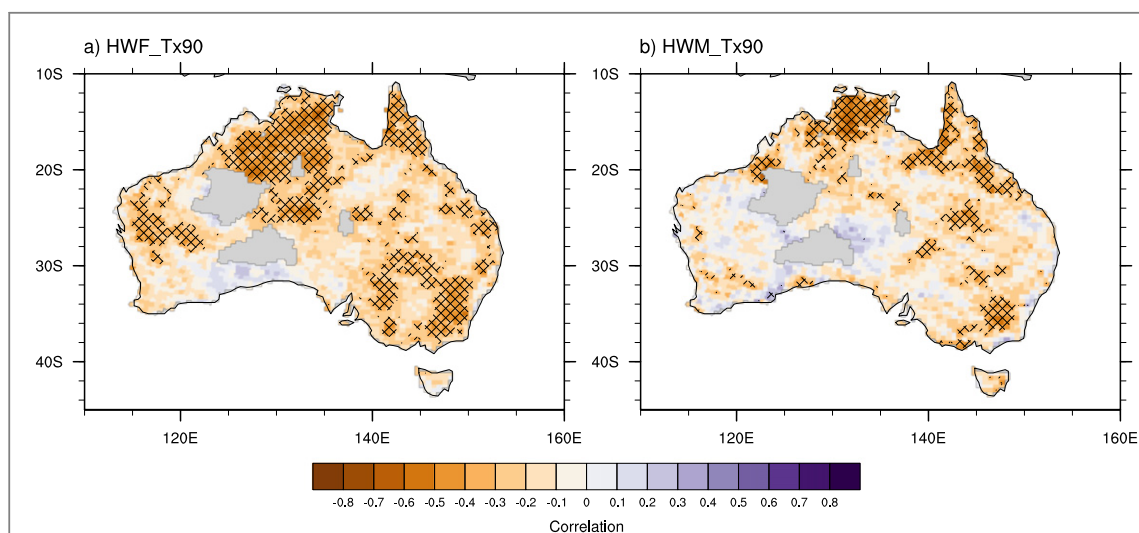
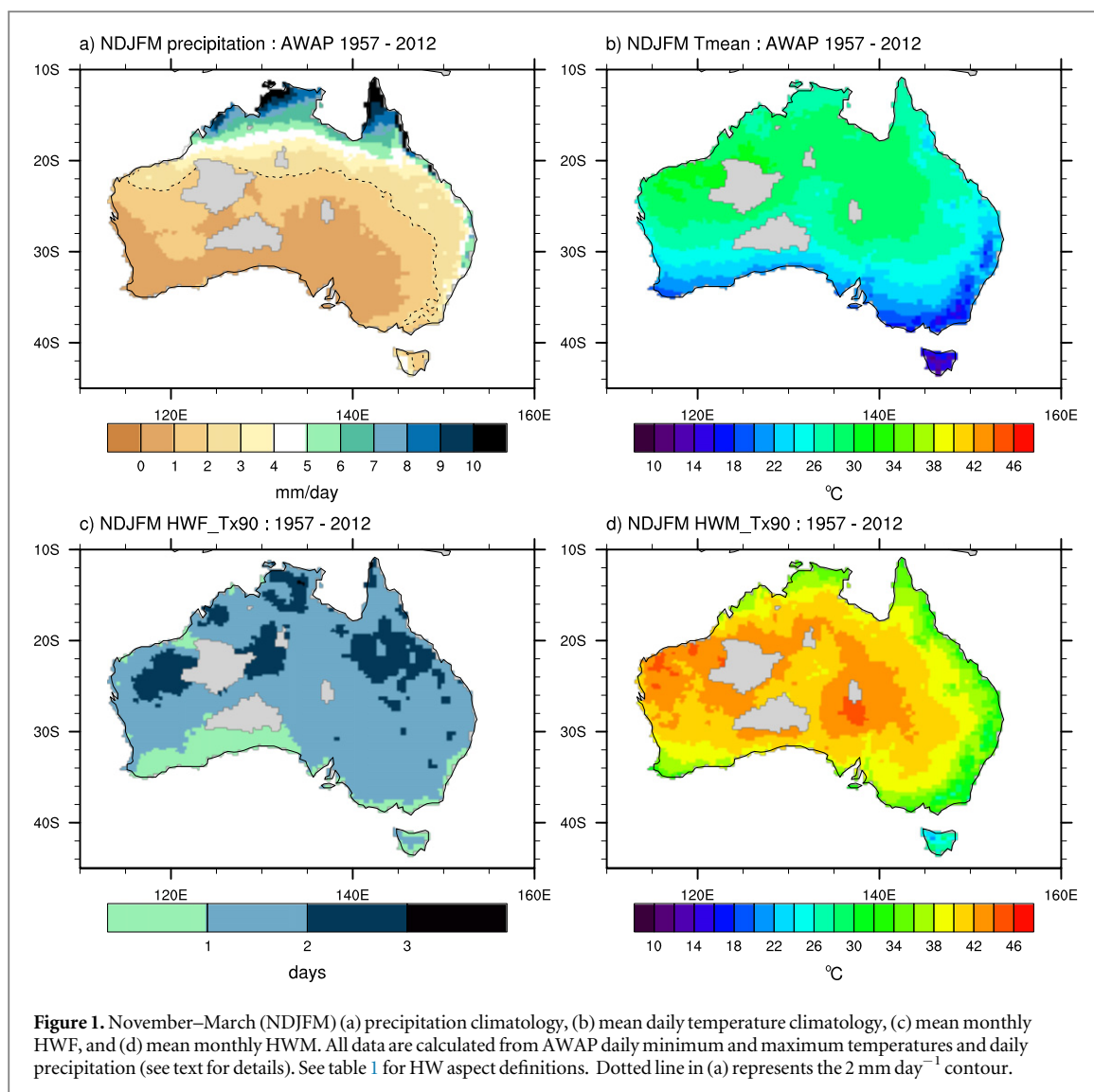
In this study we examine the relationship between all five HW aspects (table 1) from the hottest month in each extended austral summer (November–March), and the soil moisture from the preceding month (based on the 3 month SPEI described in section 2.3), for the years 1957–2012. Thus our sample size is 55. Relationships between various HW aspects and antecedent soil moisture are strongest for the Tx90 definition of HWs (i.e., based on maximum rather than minimum daily temperatures) and thus we focus on this definition for the remainder of our study. Supplementary figures show our results calculated using the Tn90 and EHF definitions of HWs. We focus on the hottest HW month each year rather than all months of the climatological summer (December–February) or extended summer (November–March)

in order to find the strongest statistical relationships. Thus, our results are limited to peak summertime HW months over the period 1957–2012. Further, we define the hottest HW month each year according to the HW aspect being assessed. For example, the hottest HW month when examining HWM is the month when HWM is highest, and the hottest HW month may be different for different HW aspects. While this means that SPEI can be different for different HW aspects in the same year, we stress that we are interested in statistical relationships between soil moisture and HWs, rather than the atmospheric drivers of different HW aspects. Defining the hottest month separately for each HW aspect ensures the strongest relationship with antecedent SPEI is found. Climatologies of observed precipitation, mean temperature, HWM and HWF are shown in figure 1.

To determine how the probability distribution of the various HW aspects respond to antecedent soil moisture we utilise quantile regression (Koenker and Bassett 1978), in a similar fashion to Hirschi *et al* (2011) and Mueller and Seneviratne (2012). Simple linear regression relates the mean of the dependent variable y to the independent variable x and assumes that higher order moments do not vary with x . Quantile regression examines how different parts of the distribution vary (i.e. dispersion) by minimising the sum of absolute residuals ($y_{\text{estimated}} - y_{\text{observed}}$) after a weighting is applied, based on the quantile of choice. In this study we use the 0.1, 0.5 and 0.9 quantiles to represent the lower, middle and upper end of the distribution of each HW aspect.

3. Results

To characterise the statistical relationship between antecedent soil moisture and the five HW aspects defined in table 1 we first determine their correlation over the period of interest (figure 2). The results of this analysis were largely similar between those HW aspects related to intensity (HWA and HWM) and those related to longevity (HWF, HWN and HWD). Because of this we only show figures of HWM and HWF, which have the strongest correlations. The climatologies are illustrated in figure 1 (see supplementary figures S2, S4 and S5 for calculations with all HW aspects). Significant anti-correlations exist for all HW aspects (two-sided, 95%) and manifest predominantly in the eastern and northern parts of the continent, where NDJFM precipitation is relatively high (figure 1(a)), and are weak in the south and west. Anti-correlations are larger for HWF and more often significant, compared to the other HW aspects. These results suggest a slightly stronger influence of antecedent soil moisture on the frequency of HW days and that antecedent soil moisture may have some predictive ability for HWs in the north and east of the continent (figure 2). When performing these correlations using SPI—and thus



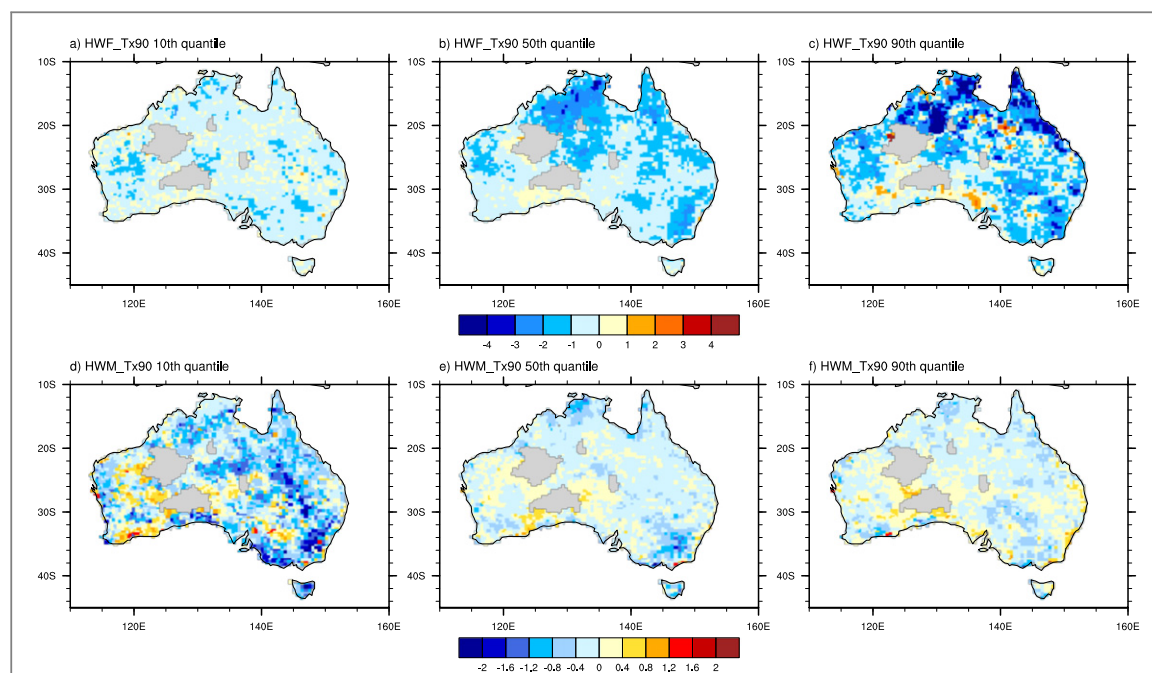


Figure 3. Regression slopes for HWF (top row) and HWM (bottom row) for the 0.1 (left column), 0.5 (middle column) and 0.9 (right column) quantiles.

neglecting the effects of evapotranspiration—the spatial patterns are similar, though they are generally weaker and less often statistically significant (see figures S2 and S3).

Figure 3 shows maps of the regression coefficients for the 0.1, 0.5 and 0.9 quantiles of HWF and HWM against antecedent soil moisture. HW aspects related to the longevity of events have the strongest relationship to antecedent soil moisture at the upper end of the distribution (90th percentile) and are overwhelmingly negative. The strongest and most homogenous relationships exist for HWF where, across the majority of the continent, months with the highest HWF exhibit the largest response to antecedent soil moisture (figures 3(a)–(c)). This response is notably stronger in the monsoon region of northern Australia. This is consistent with the results of Mueller and Seneviratne (2012) who use global reanalyses and observational datasets to show a stronger relationship for high percentiles between hot days and antecedent soil moisture. Consequently, the number of individual HW events (HWN) also increases most for months with higher HWN than for those with lower HWN, though the overall slopes are low compared to HWF (figure S4). Regions exhibiting positive regressions, particularly in upper tail responses (e.g. figure 3(c)), indicate that other factors such as prevailing meteorology can play a dominant role in HW events.

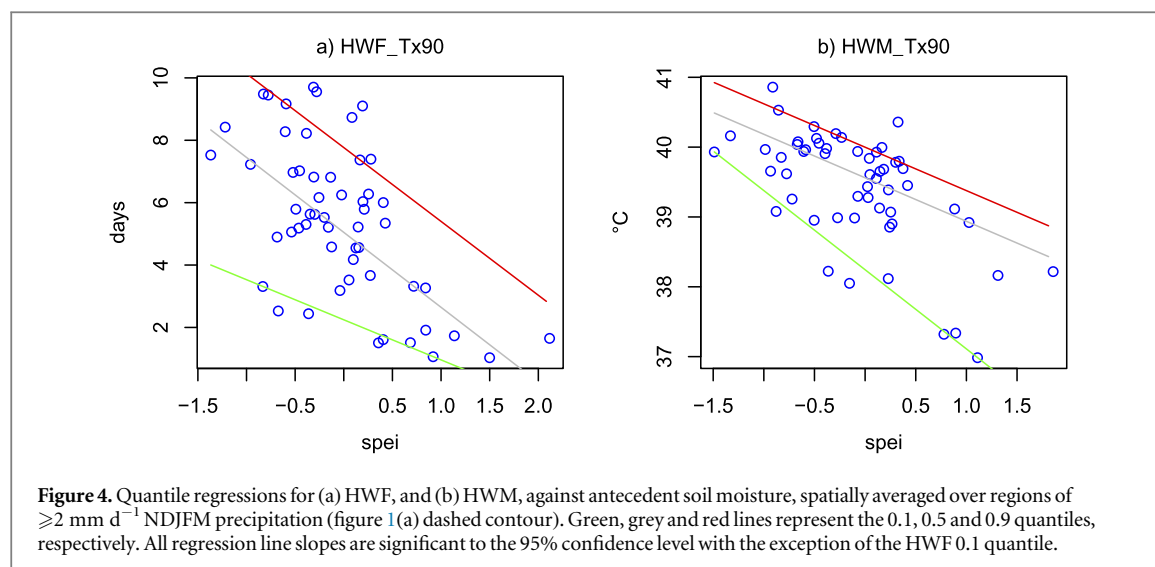
Conversely to HW aspects related to longevity, HWM exhibits stronger relationships with antecedent soil moisture at lower quantiles (figure 3(d)) and the same applies to HWA (figure S4). Regions of high summer precipitation in the east and north (figure 1(a)) also experience larger negative regressions

compared to the south and west, consistent with the higher anti-correlations in these regions (figure 2(b)). Relatively little change occurs at higher quantiles over the whole continent. Thus, over the north and east of the continent minimum HW temperatures tend to increase more than the maximum HW temperatures when antecedent soil moisture is low.

Different responses in the upper and lower tails of the distribution can be summarised by quantile regressions of the spatial means of each HW aspect onto the spatial means of the corresponding 3 month SPEI (figure 4, figure S5 for all HW aspects). While this masks spatial variations, we minimise potentially spurious effects from combining dry and wet regions by constraining our analysis to grid cells where austral summer rainfall equals or exceeds 2 mm d^{-1} (figure 1(a)). From these results it can be clearly seen that the probability distributions of HWF widens as antecedent soil moisture decreases, although for HWM it narrows as antecedent soil moisture decreases. HWA responds similarly to HWM, while HWN and HWD respond similarly to HWF (figure S5).

4. Discussion

Quantifying the response of multiple HW aspects to antecedent soil moisture has highlighted the potential importance of the latter in amplifying HW events in large parts of Australia, but moreover establishes a simple means of estimating peak summer HW frequency and intensity using the SPEI as a proxy for soil moisture.



Assessing quantile regressions of HW days against antecedent soil moisture has been undertaken previously at a regional scale for Europe (Hirschi *et al* 2011) and at a global scale (Mueller and Seneviratne 2012), however the latter study lacked substantial detail over Australia and both studies utilised SPI instead of the more relevant SPEI. Furthermore, we utilise the HW framework of PA13 which quantifies HW aspects related to both longevity and intensity, which we show differ in their response to antecedent soil moisture deficits (figure 3). Perkins *et al* (2015) recently examined these HW aspects in relation to soil moisture over Australia, however, like the above studies evapotranspiration was not included in their soil moisture balance and more pertinently they did not assess changes at the ends of the probability distribution, which we also show respond differently to changes in antecedent soil moisture.

The correlation between antecedent soil moisture and HWF (figure 2(a)) compares broadly with Mueller and Seneviratne (2012), who found significant anti-correlations in the east and north of Australia compared to the southwest (their figure 1(d)). However, substantial local differences exist compared to our study which can be associated with their use of the ERA-Interim reanalysis ($\sim 75 \text{ km} \times 75 \text{ km}$) and CRU dataset ($\sim 50 \text{ km} \times 50 \text{ km}$) for temperature and precipitation, respectively (see AWAP in this study; $\sim 50 \text{ km} \times 50 \text{ km}$), their different definition of the hottest month which was based on mean surface temperature, as well as their use of a shorter time period (1979–2010). Our use of the SPEI in this study largely affects the magnitude of the correlations but not their spatial patterns (see figures S2 and S3). The largest discrepancy between this study and Mueller and Seneviratne (2012) is that they show no significant anti-correlations over northeast Australia, which occur here for both SPEI and SPI (figures S2 and S3). Given that the AWAP dataset is based on a reasonably high density of observations in northeast Australia (see

figure 2 Jones *et al* 2009), we believe the significant anti-correlations observed in this region are robust (figure 2). The correlations of Perkins *et al* (2015) differ in spatial detail with ours even though they compare the same HW aspects used here and also utilise the AWAP dataset. Perkins *et al* (2015) exhibit more widespread significant correlations over east Australia than this study, which, based on sensitivity tests (see figures 2 and S6) can be largely attributed to the longer time period used in that study (1911–2012). The difference in spatial detail we speculate is also due to these author's correlation of HW aspects from each entire summer to the preceding June–October rainfall anomaly, while we focus on the hottest month of each summer. However, qualitatively both studies show the same relationships between soil moisture and HWs.

It is clear that the standard response to low soil moisture, whereby temperatures rise because an increasing sensible heat flux to the atmosphere compensates a decreasing latent heat flux (Alexander 2011), does not translate into increases in all HW aspects and in fact can decrease them (figures 3 and S4). A prime example is seen in the lower tail response of HWA and HWM, where large positive regression coefficients exist in western and central Australia (figure 3(d)). In regions such as this, where summer precipitation and thus soil moisture is minimal (figure 1), other factors must dominate. Soil moisture, synoptic meteorology and large scale modes of variability constitute the three primary elements that influence HWs (Perkins 2015). For example, Kala *et al* (2015) showed that an increase in soil moisture over northern Australia can in fact lead to increases in maximum temperature in southeast Australia after 10–15 days, as the perturbation acts to change the structure of the upper-level anticyclones. However, the large local heterogeneity observed here suggests factors operating at smaller spatial scales than synoptic meteorology and modes of variability must be influential. Data quality issues in AWAP may be one such

issue contributing to the heterogeneity of our results (King *et al* 2013).

Several regions experience particularly strong coupling between HWs and antecedent soil moisture. In the southeast of the continent HWF and HWM is very responsive to antecedent soil moisture changes (figures 2 and 3). This region is highly agricultural and thus application of the SPEI to the relationships identified in this study may provide a simple—if somewhat heuristic—method for informing operations during peak summer months beyond the HW forecasts provided by the Australian Bureau of Meteorology (currently out to six days). Access to up-to-date SPEI calculations is offered by the Global Drought Monitor (<http://sac.csic.es/spei/map/>). Multiple regions in northern Australia exhibit strong relationships between soil moisture and HWF (figures 2(a) and 3(c)). These regions consist mostly of small urban or rural communities. Rural communities may particularly benefit from early warning of extreme summer months, which have been shown to have a potentially disproportionate impact on indigenous inhabitants (Webb *et al* 2014, Green *et al* 2015).

5. Conclusions

There are significant statistical relationships between peak summertime HW characteristics and antecedent soil moisture over large sections of northern and eastern Australia, where summer precipitation is relatively high. When antecedent soil moisture in these regions is low the probability distribution function narrows for HW intensity, but widens for HW longevity. Three main conclusions can be drawn from the historical data examined here, pertaining to the north and east of the continent during peak summer months;

- When antecedent soil moisture is high there is little chance of experiencing high HW temperatures or numerous HW days ('high' and 'numerous' being defined by historical values, figure 4).
- When antecedent soil moisture is low there is little chance of experiencing low HW temperatures, however, the number of HW days will not necessarily be high. Thus, low soil moisture seems a necessary but not sufficient requirement for high HW days.
- In regions of minimal summer precipitation, such as the center and west of the continent, HW intensity and longevity often increase in response to high antecedent soil moisture, due possibly to a negligible role of soil moisture in these regions and/or quality issues in the AWAP dataset.

In identifying spatial relationships between soil moisture and HWs, several regions stand out as being particularly susceptible to the positive feedback caused by dry antecedent conditions and therefore may benefit the most from accurate model soil moisture initialisations. These regions may also benefit from HW predictions for peak summer months—augmenting current Bureau of Meteorology HW forecasts—based on the simple relationships identified here.

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